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SYNOPSIS: The spatial variation of seismic waves has an important effect on the seismic response of structures of extended length. Based on data collected from the SMART-1 array, the spatial variation of seismic waves can be examined. The purpose of this paper is to examine the effect of the spatial variation of seismic waves on a spatially distributed system. With the consideration of the soil amplification ratio between two sites and spatial variation of seismic waves, a ground deformation spectrum is developed from stochastic point of view. This spectrum can provide information useful in predicting maximum ground deformation. The seismic response of a spatially distribued system, such as the effects of variation in soil stiffness on the dynamic response of pipelines are discussed.

INTRODUCTION

For structures with long spans or large foundations, differential ground motion at the supports has an important effect on structural response. Seismic design of such structures differs fundamentally from that of conventional, "point" , structures. Ingeneral, earthquake ground motion at a site is controlled by the following three parameters: Source characteristics, path effects, and local site conditions. It is assumed that the ground motion at the supports of the "point" structure is essentially uniform. On the other hand, The "extended" structures extend for a long distance and their supports may undergo different motions during earthquakes. Previously, most of these studies focused only on the effects of travelling waves on the response of extended structures. Recently, data obtained from a dense array of closely spaced seismographs have provided useful information for the study of the spatial variation of seismic waves.

To examine the seismic response of spatially distributed systems, one has to study the wave passage effects, spatial variation of seismic waves, and point spectrum at a specific site. The spatial variation of ground motion may be obtained empirically from recorded data at dense instrument arrays, such as the SMART-1 array in Lotung[1]. The results show that correlation of ground motion at different points decreases as the distance between different points increases. The loss of coherence can arise from the scattering effect caused by the inhomogeneities of wave passages. Models used to demonstrate the spatial variation of ground motion are either analytical expressions fitted to data, or analytical expressions based on wave propagations[2-4]. Besides the probabilistic modelling of ground motion at a point, the cross spectral density function of ground movement between two point needs to be discussed. The proposed cross-spectral density function of free-field ground motion between different stations can be expressed as[5]

$$S_{ij}(\omega) = S_0(\omega)\ f_r(|r|,\omega)\ \exp(-i\omega r/V_a) \qquad (1)$$

in which $S_o(\omega)$ is the reference spectrum, $f_r(r, \omega)$ is the frequency-dependent spatial coherence function and V_a is the apparent wave propagation velocity. Eq.1 takes into account the wave passage effect, spatial variation of seismic waves and surface ground motion spectrum at a site.

The purpose of this paper is to study the ground deformation and the associated pipeline response. To determine the differential ground movements, the following topics are discussed; (a) local soil amplification; (b) spatial variation of seismic waves; (c) the stochastic ground motion. The local site characteristics that may influence the reference spectrum are also examined by means of the wave propagation theory and actual recored earthquake data. The analysis of differential ground movement, as it related to the stochastic modelling of ground motion and the spatial variation of seismic waves, are discussed.

DESCRIPTION OF THE SMART-1 ARRAY DATA

The design of structures of extended length, such as pipeline, bridges capable of withstanding an earthquake, must permit the joints between its parts to accommodate relative motion induced by ground motion. In examining such differential ground motion, from an experimental point of view , the data recorded by a dense array may provide valuable information. TheSMART-1 array, located at lotung, Taiwan, provides the information to study differential ground motion and local site amplification characteristics. The original array consisted of 37 forced balanced triaxial accelerometers arranged in three concentric circles. In June 1989, two additional stations, named E01 and E02(2.8km and 4.8km south of the central station on outcropping bedrock) were added to the array. The epicental locations of some large events are shown on Figure 1.

In examining differential motion, it was thought that the differential ground displacements may be partially explained as being a consequence of a phase delay in a long-period wave propagating

EVENT No.	DATE	EPICENTER		DEPTH (km)	MAG.	AZIM.	DELTA (km)
		LONGITUDE	LATITUDE				
24	1983.06.24	122-36.8E	23-58.89N	25.0	6.9	136.3	115.3
39	1986.01.16	121-57.67E	24-45.77N	10.2	6.5	63.6	22.2
40	1986.05.20	121-35.49E	24-04.90N	15.8	6.5	195.0	67.9
43	1986.07.30	121-47.65E	24-37.73N	1.6	6.2	149.1	5.8
45	1986.11.14	121-50.17E	23-57.65N	6.9	7.0	174.8	79.3

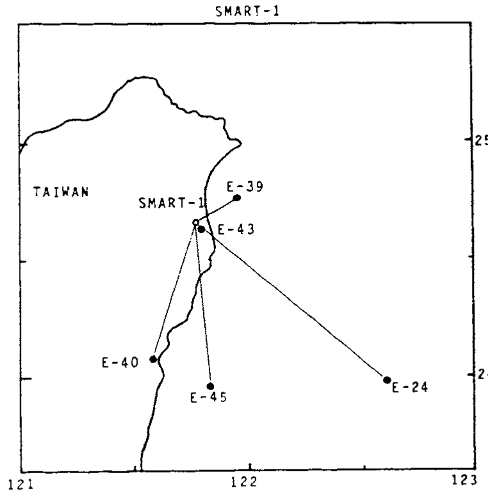

Fig.1: Epicentral location of earthquakes recorded by SMART-1 array.

across the two separate sites. If one considers sinu-soidal wave propagation in a radial direction across two sites with constant wave velocity C, the maximum relative displacement, Δy, between two sites is given by:

$$\left|\Delta y(t)\right|_{max} \approx \frac{D\,\omega_0\,\Delta x}{C} \tag{2}$$

in which D is the maximum ground displacement of the long-period wave with dominant frequency[6]. Christian pointed out that the relative displacement must be no greater than the maximum positive displacement minus tha maximum nagative displacement, that is

$$\left|\Delta y(t)\right|_{max} = \left|D_{max} - D_{min}\right| \tag{3}$$

From the study of array data (Events-39 & 40), the calculated relative ground movement was plotted as a function of separation, as shown in Fig.2. For engineering design purposes, a more general spectrum, which also takes into consideration the variation of local soil characteristics , is needed in order to predict ground deformation. Such a ground deformation spectrum will be discussed in the following section.

DIFFERENTIAL GROUND MOVEMENT

In examining seismic induced differential ground motion, it appears that phase delay in a long-period wave propagating across two locations dominates the differential movement. From the point of view of random vibration, the relative displacement $u_D(x,t)$ between two points x_1 and x_2 during an earthquake can be expressed by the power spectal density function $S_{u_D}(x,\omega)$:[7,8]

$$S_{u_D}(x,\omega) = S_{u_1}(\omega)\left\{1 + \frac{S_{u_2}(\omega)}{S_{u_1}(\omega)} - 2\,\mathrm{Re}\left[R(x,\omega)\right]\right\} \tag{4}$$

where $S_{u_1}(\omega)$ and $S_{u_2}(\omega)$ are the displacement power spectra at points x_1 and x_2, $R(r,\omega)$ is the normalized cross-spectrum. If the power spectral density function at half-space is represented as $S_0(\omega)$, and $H_1(\omega)$ are specified as the local site amplification at two different sites, then the auto-spectrum and cross-spectrum at x_1 and x_2 are specified as:

$$S_{x_1}(\omega) = \left|H_1(\omega)\right|^2 S_0(\omega)$$

$$S_{x_2}(\omega) = \left|H_2(\omega)\right|^2 S_0(\omega) \tag{5}$$

$$S_{x_1x_2}(\omega) = \left|H_1(\omega)\right|\left|H_2(\omega)\right| S_0(\omega)\, f_x(|x|,\omega)\, \exp\left[\frac{-i\omega x}{V_s(\omega)}\right]$$

where the spatial variation coherence function $f_x(x,\omega)$ and wave passage effect (with apparent wave velocity $V(\omega)$) are applied to the cross-spectrum. If Eq.4 is substituted into Eq.3, the spectral density of relative ground displacement can be expressed as

$$S_{u_D}(x,\omega) = \left|H_1(\omega)\right|^2 S_0(\omega)\left\{1 + \frac{|H_2(\omega)|^2}{|H_1(\omega)|^2} - 2\,\frac{|H_2(\omega)|}{|H_1(\omega)|}\, f_x(|x|,\omega)\, \cos\left[\frac{\omega x}{V_s(\omega)}\right]\right\} \tag{6}$$

The ratio of site amplification $|H_2(\omega)|/|H_1(\omega)|$, spatial coherence function f(.), and apparent phase velocity $V_s(\omega)$ are three important factors that may have significant influence on the estimation of relative ground displacement.

SITE AMPLIFICATION RATIO

It is generally accepted that a particular surface accelerogram reflects, to some degree, the characteristics of the near-surface soil layer at the recording site. In most practical cases, a soil surface spectrum can be obtained by multiplying an assigned rock spectrum with a soil

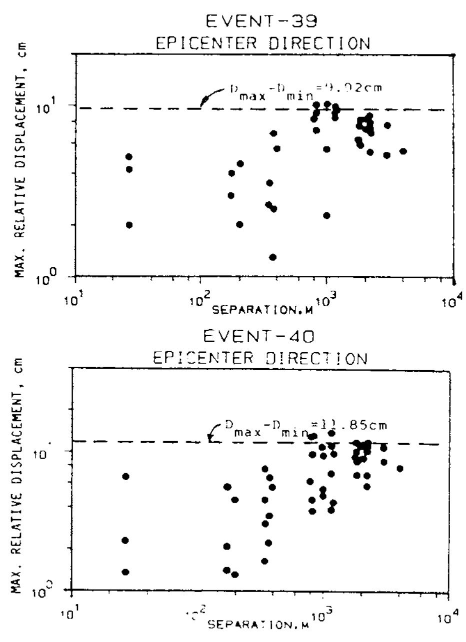

Fig. 2: Plot of maximum relative displacement with respect to station separation (Events-39 & 40, epicentral direction).

amplification function. Generally speaking, the overall shapes of the amplification function are not similar for different earthquakes. This indicates that motion on the free surface is sensitive to the depth and distance of source, as well as to the type of source. In order to study the relationship between the relatively soft subsurface and strong ground motion, a one-dimensional model[9,10] which models inclined propagating SH, P and SV waves in a horizontal-layered structure, is examined. The subsurface soil conditions were modelled on the SMART-1 array site, as shown in Fig.3. The transfer function between the free surface and the half-space outcrop for a single inclined SH wave, and a combination of inclined P and SV waves from the half-space at different incident angles are examined, as shown in Fig.3. It is clear that the transfer function is significantly influenced by the wavetype and direction of incidence at the half-space of bedrock, especially in the high frequency range. Whenever possible, real data should be used to estimate local site effects and this data should be for events having different angles of incidence, wave types and source distances.

SOIL PROPERTIES OF SMART-1 SITE

DEPTH (m)	Vp (m/sec)	Vs (m/sec)	ρ	G kg/cm²	Q-VALUE
0 ~ 8	187	110	1.800	312	10
8 ~ 31	289	170	1.800	776	10
31 ~ 48	391	230	1.800	1294	10
48 ~200	680	400	1.800	1610	10
200 ~∞	1836	1080	2.500	42320	100

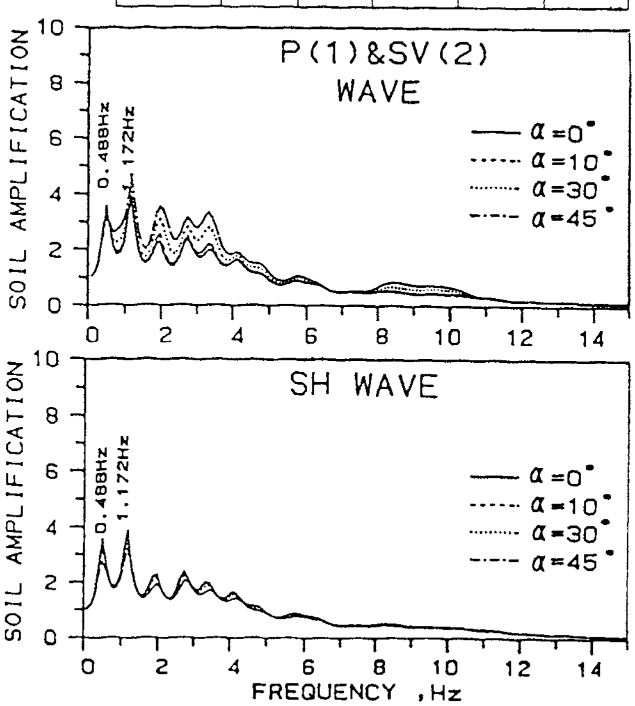

Fig.3: Analytical results of soil amplification, (a) Soil profile of SMART-1 array site; (b) Incident P(=1) and SV(=2) waves; (c) incident SH waves.

The site amplification ratio represents the variation of site conditions between two points on a ground surface. The semi-empirical formula for the seismic characteristics of the ground, developed by Kanai,[11] was adopted. The site amplification ratio is then expressed by

$$\frac{|H_2(\omega)|}{|H_1(\omega)|}=\frac{\left\{\left[1-\left(\frac{T}{T_1}\right)^2\right]^2+\left[\frac{0.2}{\sqrt{T_1}}\left(\frac{T}{T_1}\right)^2\right]\right\}^{1/2}}{\left\{\left[1-\left(\frac{T}{T_2}\right)^2\right]^2+\left[\frac{0.2}{\sqrt{T_2}}\left(\frac{T}{T_2}\right)^2\right]\right\}^{1/2}} \quad (7)$$

where T_i is the dominant period of the local site characteristics at station i. The accuracy of this formula is shown by comparison actual data. Data from station007 and 001(with a separation of 4km) were used to calculate the amplification ratio, and compared with the empirical model, as shown in Fig.4.

SPATIAL COHERENCE OF SEISMIC WAVES

Functions that describe the manner in which spatial coherence of ground motion decreases with frequency and with spatial separation of observation points have been proposed by many researchers.[12,13] This measured frequency-dependent coherence of the spatial correlation function of seismic waves is independent of wave propagation directionality. In this paper, the direction defined by the line connecting the two stations with the direction of wave incidence is considered a function in the spatial variation of seismic waves. An empirical model for the spatial variation of ground motion is provided. The frequency dependent directionality of the spatial correlation function can be defined empirically as:[14]

$$f_r(r,\theta,f)=\exp\left\{-r\,(\tilde{a}\cos^2\theta+\tilde{b}\sin^2\theta)^{1/2}\right\} \quad (8)$$

in which r defines the saparation, θ is the relative angle, a and b atr frequency dependent parameters. These parameters can be estimated by matching the calculated spatial coherence in an iso-coherence map with the proposed model through minimization technique for each discrete frequency.

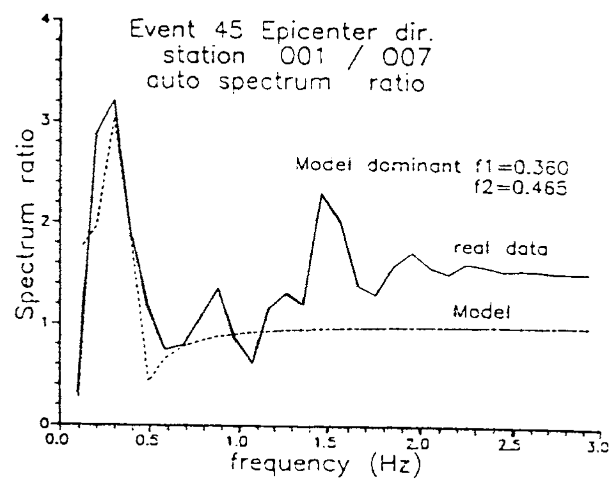

Fig.4: Comparison in soil amplification ratio between empirical model and results from data analysis(Ratio between Station 007 and Station 001).

GROUND DEFORMATION SPECTRA:

The power spectral density function of relative ground displacement, $S_{u_D}(r,\omega)$, has been developed on the basis of the phase delay ina long-period wave propagating between two locations, physical ground motion spectrum, and the spatial variation of seismic waves. The root mena square values of relative displacement can then be expressed as the square root of the zeroth order moment of the relative displacement power spectrum:

$$\sigma_{u_D} = \left[2 \int_0^\infty S_{u_D}(r,\omega)\, d\omega\right]^{1/2} \qquad (9)$$

Let $u_D(r,t)$ be a stationary Gaussian process, the expected value of the peak response in terms of σ_{u_D} is given by:

$$u_D(r,t)\Big|_{max} = \sigma_{u_D} \cdot p_f \qquad (10)$$

in which p_f is the peak factor which can be determined from statistics of extremes.[15] Ground deformation spectra can then be determined by normalizating the mean maximum relative ground displacement with respect to the root-mean-square value of ground displacement. Figure 5 shows the plot of ground deformation spectra for data of Event-45 recorded by SMART-1 array based on the idea just proposed. A comparison between the data and the model is also shown in this figure. It is found that the deformation spectra are very sensitive to the influence of the effect of site amplification ratio. With a short separation, the effect of site amplification is not as important in predicting the deformation spectra as it is with a large separation. The data for Event-45, also shown in Fig.5, involves a separation of less than 0.5km, and the effects of site characteristics are not obvious. From this study it is clear that four factors may influence the prediction of ground deformation spectra i.e. the site amplification ratio, the effects of wave passage, the spatial variation of seismic waves, and the reference spectrum. In this study the reference spectrum was modelled on the Kanai-Tajimi spectrum with a modification on local soil amplification. Fig.6a shows the model parameters

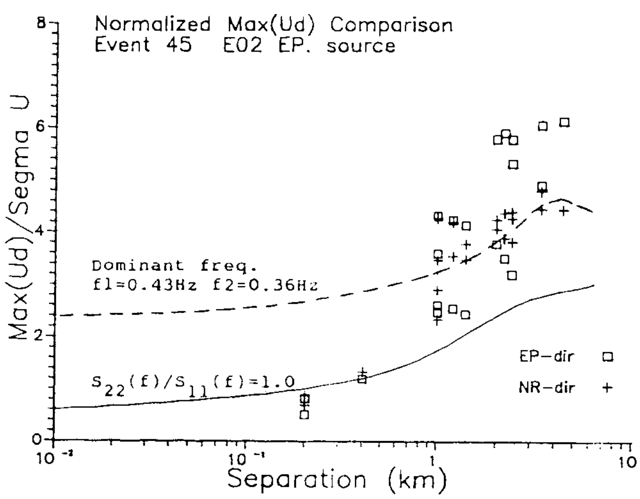

Fig. 5: Plot of Max(u_D)/σ_u with respect to separation for data of Event-45. Dash line shows the analytical result with nonuniform soil layer, and solid line shows the results of uniform layer.

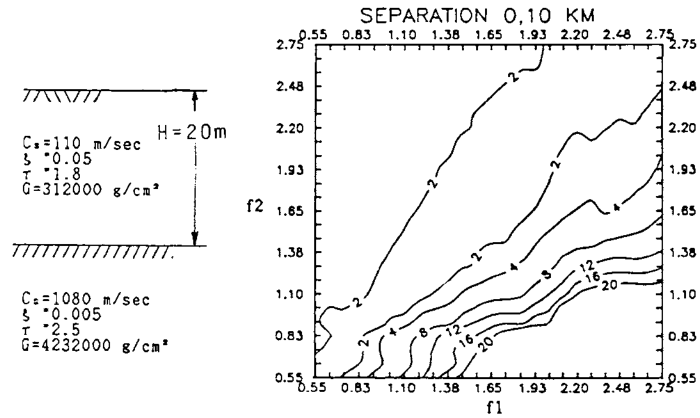

Fig.6: Variation of soil dominant frequency between two sites to the estimation of ground deformation spectra, (Iso-deformation spectra).

of local soil amplification. Variation in site amplification is derived mainly from variation in the local soil stiffness between two sites. Fig. 6b shows the iso-deformation spectra as a function of the dominant frequency between two sites. It is clear that for waves coming from a hard site(larger dominant frequency f_1) to a soft site (smaller dominant frequency f_2), the estimated deformation spectral value shows a significant increase. Fig.7 shows the sensitivity result of ground deformation spectra. Variation in local soil amplification ratio is the main effects to cause the variation in this spectra.

EFFECT OF LOCAL INHOMOGENEITY ON THE DYNAMIC RESPONSE OF PIPELINES

Dynamic response of long segmented pipelines due to a variety of seismic waves has been studied by many researchers. In general, a local inhomogeneity is one of the important factors that may contributed to a change in pipeline response. This local inhomogeneity may include a variation in free-field wave forms or a variation in local soil stiffness. The simplest model which can include a variation in soil stiffness is the two degree of freedom system shown in Fig.8. The joint displacement of this simple model is the sum of the two model contributions, $\triangle x^{(1)}$ $\triangle x^{(2)}$

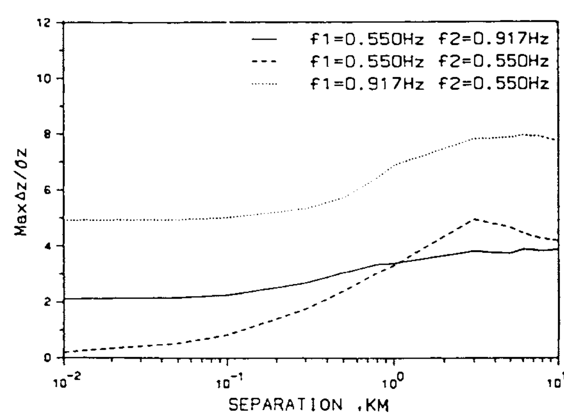

Fig. 7: Ground deformation spectra; Solid line: waves from soft(f=0.55Hz) to hard(f=0.917Hz), Light dash: wave from hard(f=0.917Hz) to soft(f=0.55Hz), Dark dash: wave in uniform soil.

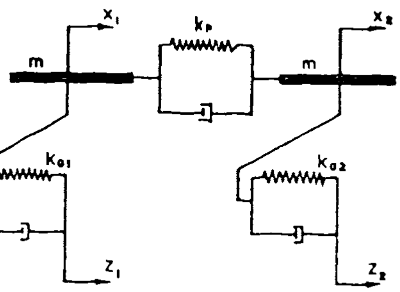

Fig. 8: Two-degree-of-freedom system of buried pipeline.

$$\Delta X(t) = \Delta x^{(1)} + \Delta x^{(2)}$$

$$= P_1 \left[R_{\overline{Z}}(t,\omega_1,\xi_1) - R_{\overline{Z}}(t,\omega_2,\xi_2)\right] + Q_1\, R_{\Delta Z}(t,\omega_1,\xi_1) + Q_2\, R_{\Delta Z}(t,\omega_2,\xi_2) \quad (11)$$

where P_k and Q_k are the modal participation facters for the coherent and incoherent ground motion of k-th mode, and $R_{\overline{Z}}(t)$ and $R_{\Delta Z}(t)$ are the solution of the following two equations:[16]

$$R_{\Delta Z_m} + 2\omega_k \xi_k \dot{R}_{\Delta Z_m} + \omega_k^2 R_{\Delta Z_m} = \omega_k^2 \Delta Z_m(t) + 2\omega_k \xi_k \Delta \dot{Z}_m(t)$$
$$R_{\overline{Z}_m} + 2\omega_k \xi_k \dot{R}_{\overline{Z}_m} + \omega_k^2 R_{\overline{Z}_m} = \omega_k^2 \overline{Z}_m(t) + 2\omega_k \xi_k \dot{\overline{Z}}_m(t) \quad (12)$$

in which $\overline{Z}_m$ and ΔZ_m are the mean and relative input ground movement between two adjacent points Recalling Eq. 12 , the interference response spectrum $S_I(\omega_0,\xi_0)$ is defined as the maximum value of $R_{\Delta Z}(t)$,

$$S_I(\omega_i,\xi_i) = \text{Max } R_{\Delta Z}(t,\omega_i,\xi_i) \quad ; \quad i = 1,2 \quad (13)$$

and the absolute displacement spectrum $S_D{}^A(\omega_0,\xi_0)$ is given as the maximum value of $R_{\overline{Z}}(t)$,

$$S_D^A(\omega_i,\xi_i) = \text{Max } R_{\overline{Z}}(\omega_i,\xi_i,t) \quad ; \quad i = 1,2 \quad (14)$$

the total joint displacement is bounded by

$$\text{Max } |\Delta x| \le P_1 \left[S_D^A(\omega_1,\xi_1) + S_D^A(\omega_2,\xi_2)\right] + |Q_1|\, S_I(\omega_1,\xi_1) + Q_2\, S_I(\omega_2,\xi_2) \quad (15)$$

$S_D^A(\omega,\xi)$ and $S_I(\omega,\xi)$ can also be determined by multiplying the peak factor and the root-mean-square value of the zeroth order spectral moment of the coherent and incoherent input motions. As discussed before, the dominant frequencies of local soil deposit at two different sites signifficantly influence the estimation of the response. Fig.9 shows the iso-meansquare value of the estimated interference response spectrum and the absolute displacement spectrum as a function of the dominant frequencies at two sites. The pipeline system was assumed to have a natural frequency of 1.0Hz and a 5% structural damping ratio. It is also found that the nonhomogeneity of soil stiffness between two sites is more important than the spatial variation of seismic waves in the study of relative motion of a pipeline segment in non-homogeneity soil deposit.

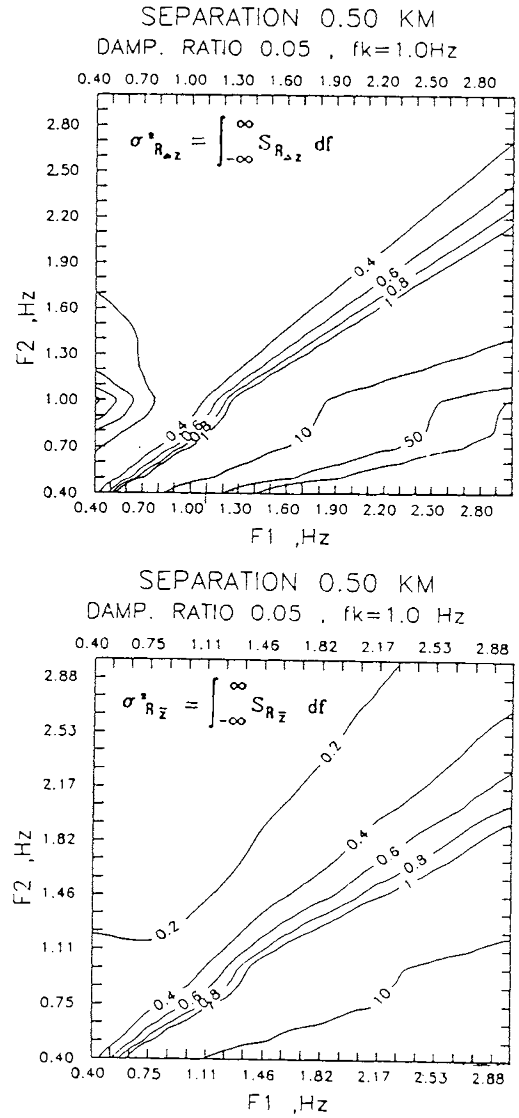

Fig.9: Variation of dominant frequencies of two sites to the estimation of mean square response; (a) Interference response spectrum, (b) Absolute displacement spectrum (the value on each contour line is the mean square value).

The relative displacement between two adjacent points of a pipeline was studied through random vibration approach. The design of a pipeline system may be dictated by future earthquakes producing the maximum response for a given geological condition. This section is aimed at examining the maximum relative displacement of a pipeline along the longitudinal direction based on linear elastic analysis; especially the effect of the epicentral direction of an earthquake on the maximum response is investigated.

SENSITIVITY OF MAXIMUM RESPONSE TO EPICENTRAL DIRECTION

Suppose a pipeline structure is constructed along the x-direction making an angle ϕ with respect to the epicentral direction ($\bar{x}$- direction), as shown in Fig. 10. The ground acceleration along the x-direction is represented as

$$x(t) = \tilde{x}(t)\cos\phi - \tilde{y}(t)\sin\phi \quad (16)$$

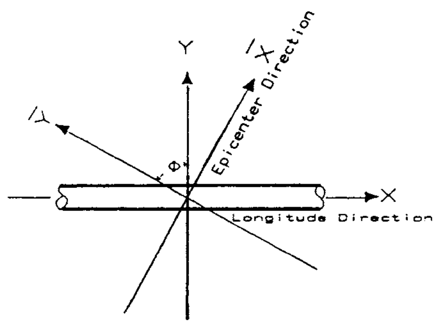

Fig.10: Coordinate relationship between pipeline direction and epicentral direction.

in which x(t) is the ground acceleration along the pipeline direction, and ϕ is the structural orientation with respect to the epicentral direction. If the duration of the strong motion part of the earthquake is much longer than the fundamental period of the ground motion, the earthquake motions may be modeld as a stationary random process. The power spectral density of the ground acceleration along the x-direction can be represented as

$$S_{xx}(\omega) = S_{\tilde{x}\tilde{x}}(\omega)\cos^2\phi + S_{\tilde{y}\tilde{y}}(\omega)\sin^2\phi - 2\mathrm{Re}[S_{\tilde{x}\tilde{y}}(\omega)]\cos\phi\sin\phi \qquad (17)$$

where $\tilde{x}$ is the epicentral direction, and $\tilde{y}$ is normat to the epicentral direction, Re(·) is the real part of the cross-spectral density between the $\tilde{x}$ and $\tilde{y}$ motions. $S_{\tilde{x}\tilde{x}}(\omega)$ and $S_{\tilde{y}\tilde{y}}(\omega)$ are the power spectral dendity function along and normal to the epicentral direction.

Let the ground motion in $\tilde{x}$ and $\tilde{y}$ directions be stationary processes that characterized by the spectral density $S(\omega)$. The spectral density of the ground acceleration may be assumed to be of the following form:

$$S_{\tilde{y}\tilde{y}}(\omega) = S_{\tilde{o}\tilde{y}} \frac{1 + 4\xi_3^2(\frac{\omega}{\omega_3})^2}{[1 - (\frac{\omega}{\omega_3})^2]^2 + 4\xi_3^2(\frac{\omega}{\omega_3})^2} \frac{(\frac{\omega}{\omega_4})^4}{[1 - (\frac{\omega}{\omega_4})^2]^2 + 4\xi_4^2(\frac{\omega}{\omega_4})^2} \qquad (18)$$

Same form can be shown for $S_{\tilde{x}\tilde{x}}(\omega)$. The cross spectral density function between $\tilde{x}$ and $\tilde{y}$ is represented as:

$$\mathrm{Re}[S_{\tilde{x}\tilde{y}}(\omega)] = q(\omega) \cdot \sqrt{S_{\tilde{x}\tilde{x}}(\omega)S_{\tilde{y}\tilde{y}}(\omega)} \qquad (19)$$

where

$$q(\omega) = \frac{\mathrm{Re}[S_{\tilde{x}\tilde{y}}(\omega)]}{\sqrt{S_{\tilde{x}\tilde{x}}(\omega) \cdot S_{\tilde{y}\tilde{y}}(\omega)}} \qquad (20)$$

Based on the finite difference model of a long pipeline, as shown in Fig.8, the equation of motion of a structural element is represented as:

$$\Delta\ddot{y} + 2\xi_n\omega_n\Delta\dot{y} + \omega_n^2\Delta y = -\Delta\ddot{z} \qquad (21)$$

It is assumed that the joint between pipe segment is soft, and Δy is the relative displacement of the pipeline element, Δz is the relative motion for input ground motion between two points. The spectral density function of relative ground input motion can be expressed as the auto- and cross-spectral density functions of the ground motions at two adjacent elements.

The mean square response of the relative displacement of two consecutive structural elements can be obtained from random vibration analysis. The information required to perform a response analysis are the spectral density of the input acceleration, the frequency response function, and the angle of structural orientation with respect to the epicentral direction ϕ. Fig.11 shows the change of root-mean-square value of relative displacement of joint motion with respect to the epicentral direction. Fig.11a shows the effect of separation to the response of roo-mean-square valy, and Fig.11b shows the effect of system natural frequency .

CONCLUSION

The purpose of this study is to determine the effects of spatial variation of seismic waves and the nonhomogeneity of soil stiffness on ground movement and on duried pipelines. A two-dimensional model of spatial coherence of seismic wave was used as a part of input motions. This spatial coherence function can be implanted into the cross spectral density function in order to analyze the relative ground movement. In examining the seismic induced differential ground motion, the site amplification ratio, the spatial coherence function, and the reference input spectrum play an important role in this analysis. The site amplification ratio is derived from nonhomogeneity of site conditions between two sites. Based on these factors, a ground deformation spectrua was developed. With the information obtained from the model and the data collected from the array, the present study gives a good estimation of ground deformation. The nonhomogeneity of soil stiffness between two sites shows a significant effect on the prediction of ground deformation. It is concluded that a large variation in soil stiffness may emphasize the ground deformation for a small separation, and a small variation in soil stiffness may de-emphasize the ground deformation for large separation.

Since the wave passage effect and the ground

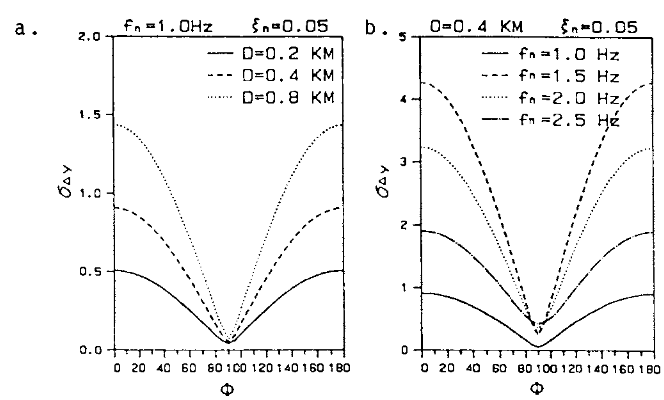

Fig. 11: Variation of Root-mean-square response of relative displacement with respect to ϕ, (a) effect of separation,D; (b) effect of system natural frequency, f_n.

motion incoherent effect are two important factors in the study of the seismic response of spatially distributed systems, the dynamic response of buried pipeline were examined. The following conclusions are drawn:

(1) Differential ground movement induced by earthquakes were examined. Tehoratical development of ground deformation spectra was studied. The nonhomogeneity of soil stiffness to the influence of deformation spectra is quite significant, especially for short separation.
(2) Spatial variation of seismic waves were included in the analysis of ground deformation. This effect is not so obvious for studying the ground deformation spectra especially for short separation.
(3) The variation in soil stiffness between two sites has a more significant effect on the relative mevement between two pipeline segments tha the spatial variation of seismic waves.
(4) The maximum response of relative motion of pipeline segments is sensitive to the epicentral direction of earthquake.

ACKNOWLEDGMENT

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